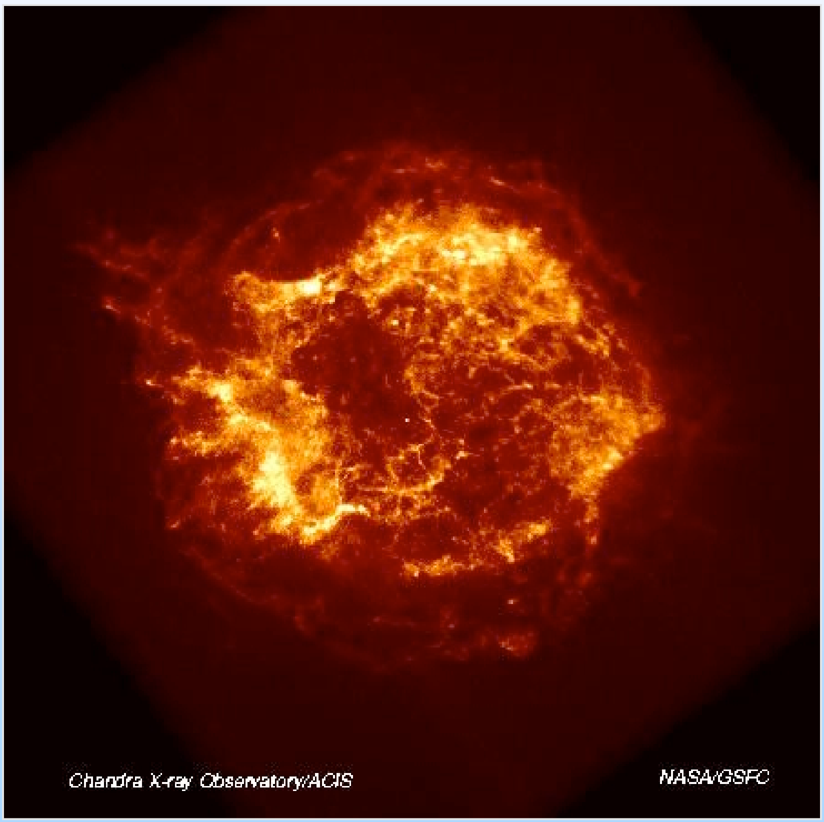
How did Cassiopeia A Explode?

Martin Laming (NRL) & Una Hwang (GSFC)



Youngest known galactic SNR.

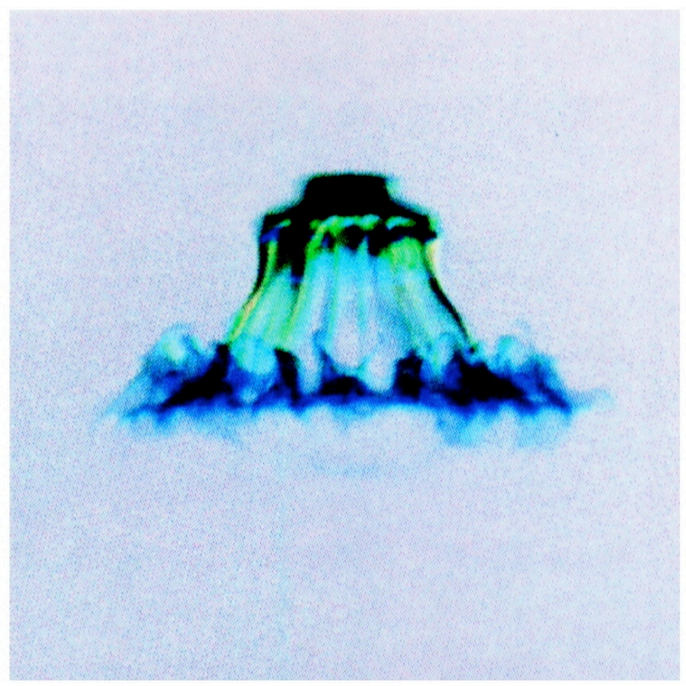
Well studied at all energies.

D = 3.4 kpc, explosion 1680 AD, forward shock speed 5000-6000 km/s, radius = 2.5 pc (assumed constant for this talk).

Ratio forward/reverse shock radii = 1.5 – 1.8 (i.e. varies).

Ejecta dominate X-ray emission in Cas A, often appear in knots.

Rationale: Shock-Knot Interactions



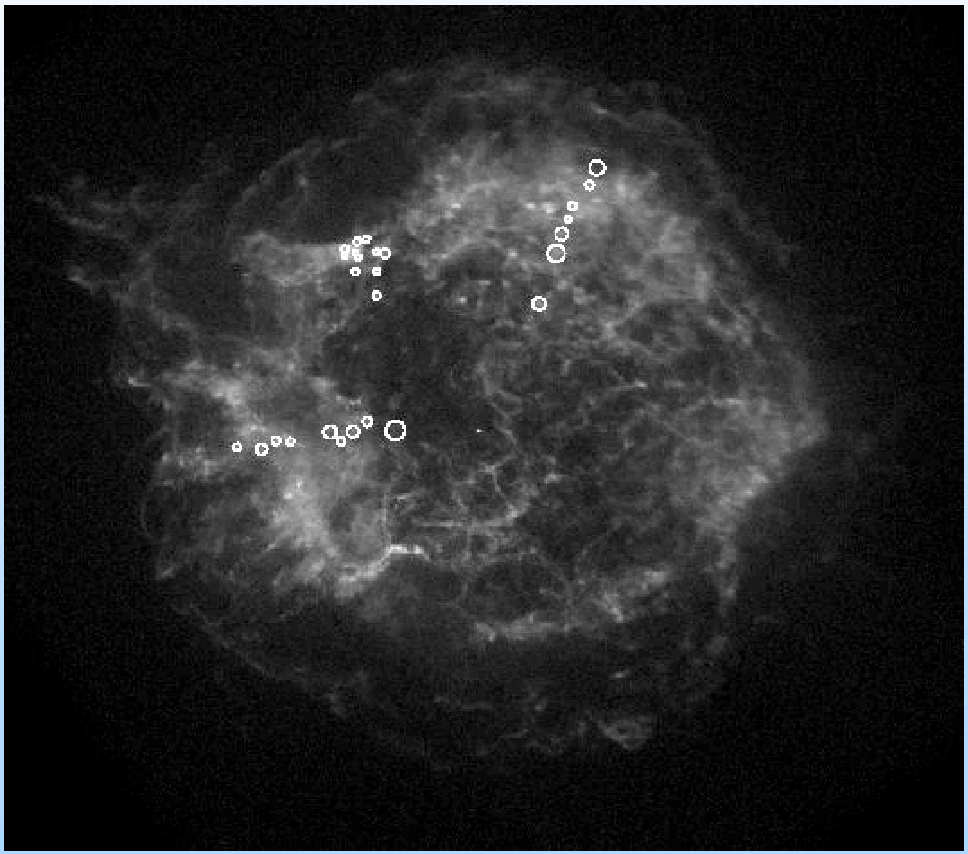
from Klein et al. 2003, ApJ, 583, 245 (@ $3t_{cc}$).

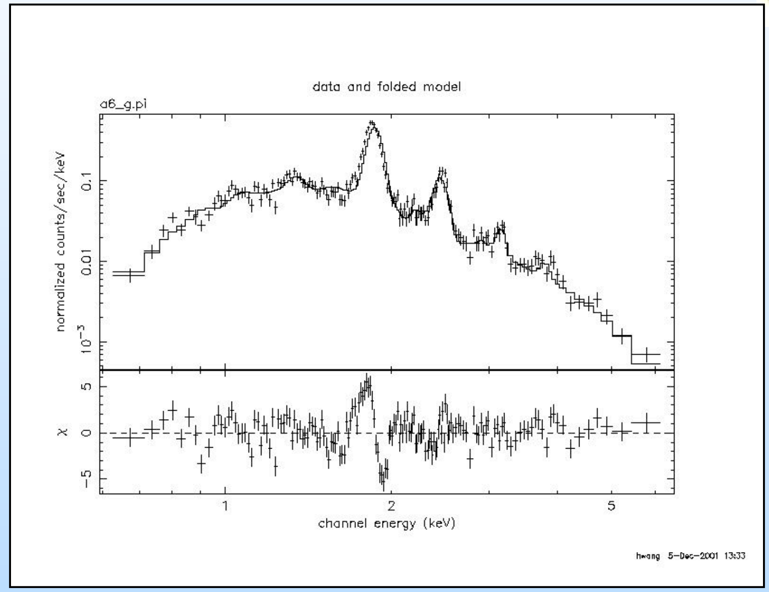
Size scale of knots is: 1" ~ 0.02 pc
At velocity 1000 km/s, time for reverse shock to cross a knot is:
20 yr << 320 yr (age of remnant).

Significantly overdense knots will not survive hydro instabilities to be seen ~300 years later!

Fit single ionization ages to knot spectra. We also fit single temperatures.

Spectral Analysis, 3 Radial Series of O rich Knots





Radial series of knots in Cas A and typical spectrum. Si, S, Ar, Ca lines and O continuum dominate.

Hydrodynamic Models

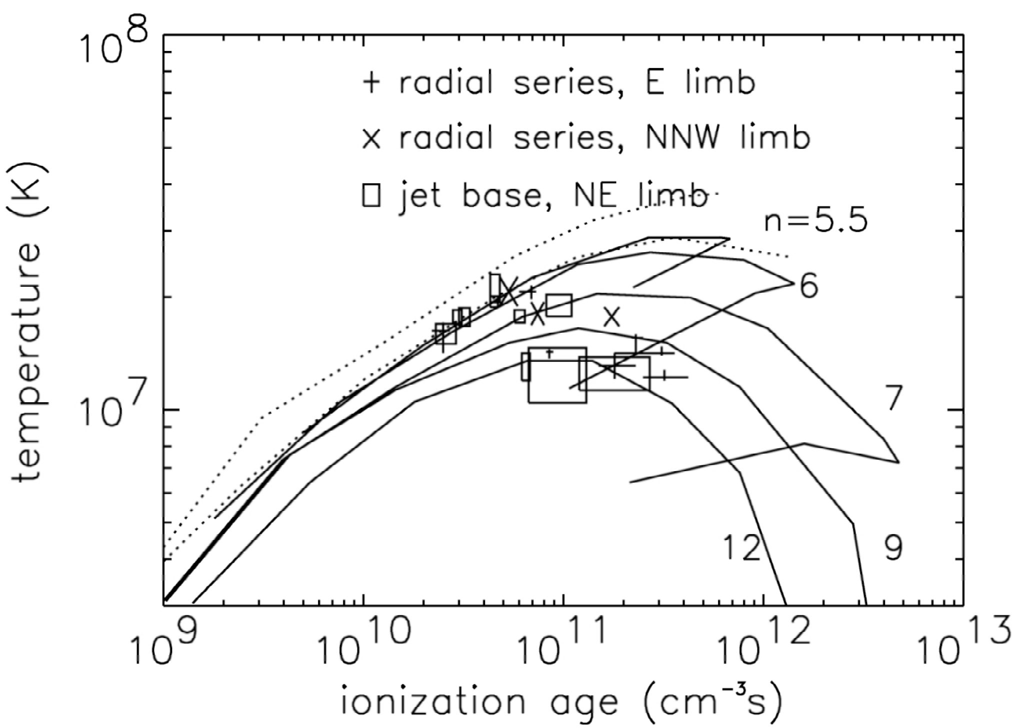
Analytical approximations of Truelove & McKee (1995) extended for circumstellar wind medium, density $\sim 1/r^2$.

Time dependent ionization balance,
Electron-ion temperature equilibration via Coulomb collisions,
Radiative and adiabatic losses,
Ejecta with uniform density core/power law envelope, $r \sim r^{-n}$.

Adjust explosion energy, ambient density, ejecta mass, n, …

Match forward shock velocity, radius and shocked CSM emission measure ($n_e^2 V$).

Results: O rich Knots

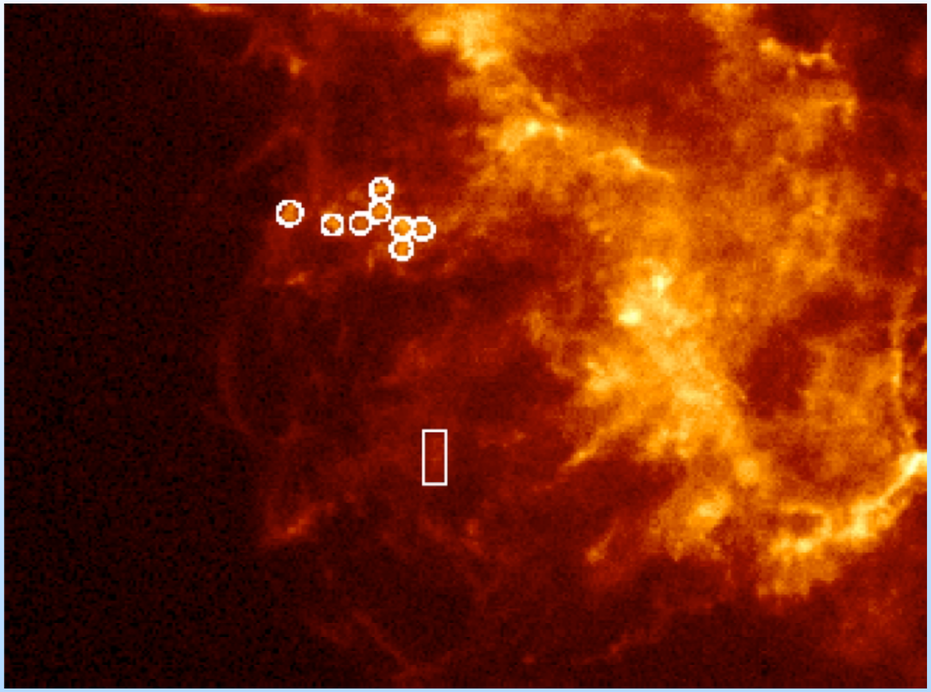


The figure shows T_e against $n_e t$ for varying ejecta envelope power laws. The models are pure O and have:

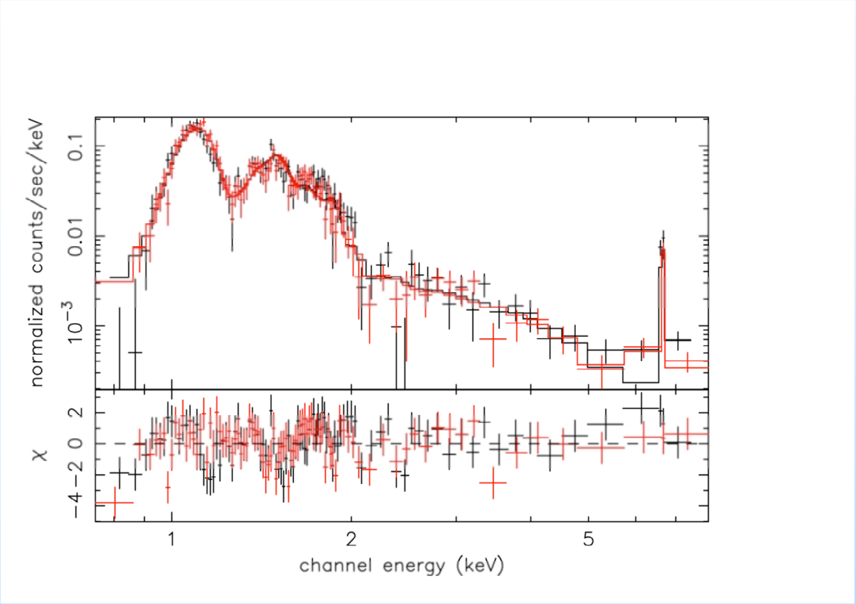
Ejecta mass = $2M_{Sun}$
K.E. = 2 x 10^{51}ergs
Dens. x r_b^2
= 14 H atoms $cm^{-3}pc^2$

Jet base knots favour n=6, higher n elsewhere.

Spectral Analysis: Fe knots and clouds

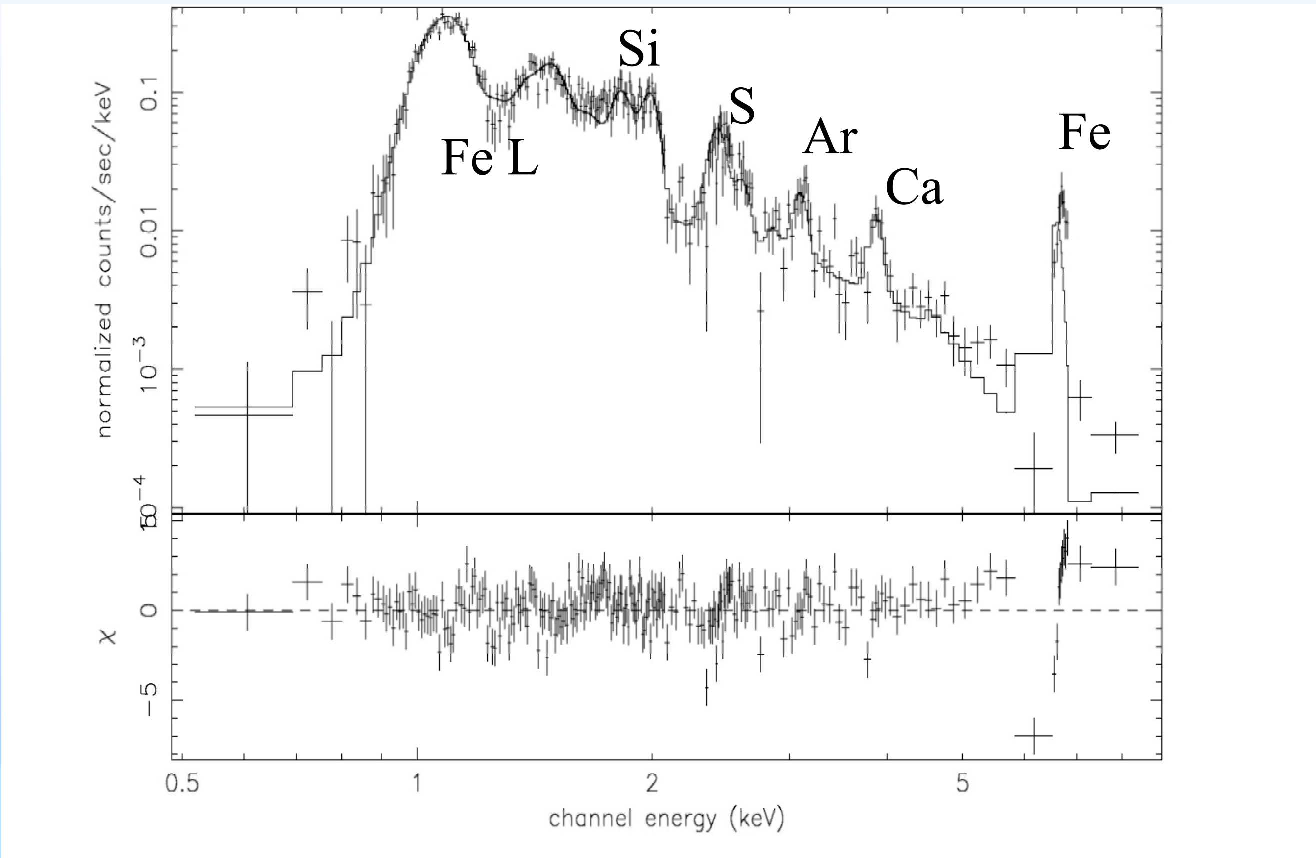


Positions of Fe knots (o) and diffuse cloud (box) on E limb.



Fit to spectra from diffuse cloud, 2000 obs (red), 2002 obs (black). Note the almost pure Fe emission.

Spectrum of Fe rich knots, local bkgd subtracted, fit with Si, S, Ar, Ca, Fe.

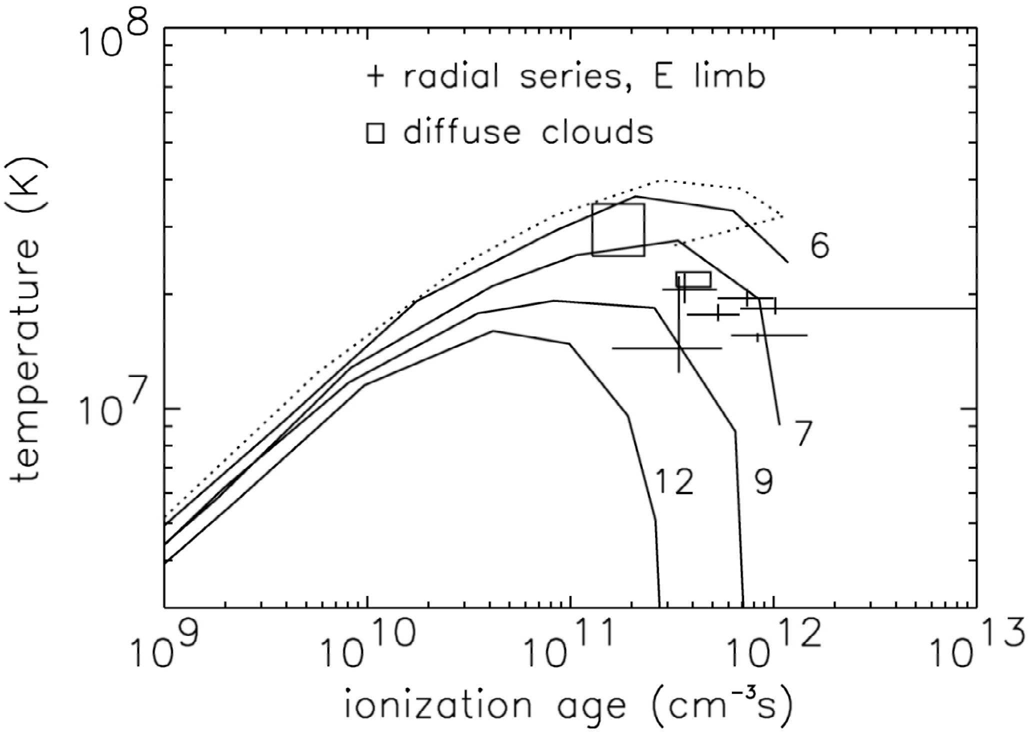


Fe/Si=2.7 solar by number,

n_et=7e11 s/cm^3 kT=1.6 keV

Looks like explosive Si burning

Results: Fe rich Knots



T_e against $n_e t$ with Fe:Si composition 9:1 by mass.

Knot $n_e t$'s place them 0.7-0.9 M_{sun} out into the ejecta (mass coordinate ~ 2 M_{sun} including compact remnant), i.e., well outside inner Fe core.

Diffuse clouds are almost pure Fe, sites of alpha-rich freezeout?

Presupernova element distribution

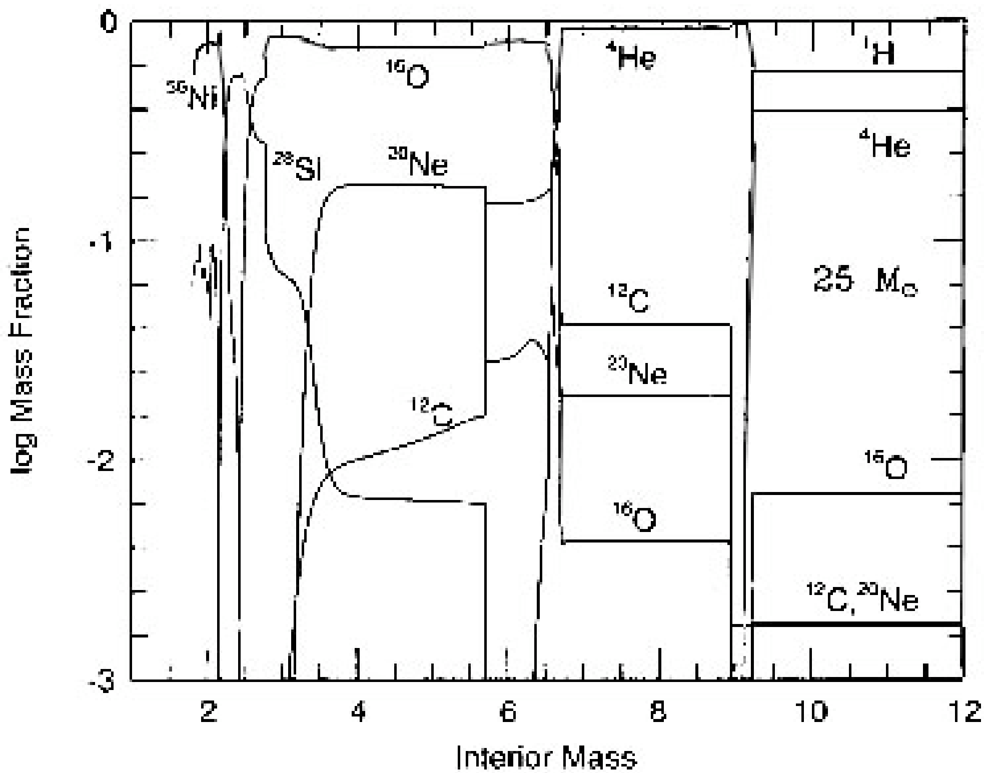


FIG. 10b

Woosley & Weaver 1995, ApJS, 101, 181, inner 12 M_{sun} of 25 M_{sun} star (similar to Cas A?).

^{44}Ti formed around M=2, so existence in SiC grains implies mixing of Fe/Ti out to M=3-4 or so.

Future Work

- More accurate shock velocities & radii, (Delaney & Rudnick).
- More elements in cooling calculations, collisionless electron-ion equilibration.
- Initial phase of expansion into tenuous W-R wind.
- Try extension of method to jet knots (might not work!), to other SNRs (e.g. Tycho), and to future SNR obs. (e.g. with Con-X).
- Fe knots need much better statistics. Chandra exposure needed to fully exploit spatial resolution is (funnily enough) ~ 1 million seconds, so …
- Chandra VLP (Hwang, Laming, Vink, Hughes, Smith, Fesen, Morse, Fryer).

Circumstellar Medium

Some evidence and arguments in support of CSM:

The optically emitting ejecta are the densest ejecta in CasA, from the core-envelope boundary. These are shocked at high enough density to become optically emitting via thermal instability if the remnant is expanding into a circumstellar wind but not into a uniform environment.

Optical emission from slow-moving quasi-stationary flocculi that are understood to be debris of the progenitor's outer layer.

Characteristics of nonthermal emission (Vink & Laming 2003).

Table of Hydro Models for Cas A

Table 1. Cas A Ejecta Profile Models $M_{ej} = 2M_\odot$, $E_{51} = 2$, $\rho r_b^2 = 14$

n	v_b (320yrs) km s^{-1}	r_b (320yrs) pc	η[a]	r_r (320yrs) pc	r_b/r_r	v_{core}[b] km s^{-1}	t_{core}[c] yrs	t_{conn}[d] yrs	t_{rad}[e] yrs	M_{rad}[f] $M_\odot$
5.5	3928	1.79	0.72	1.08	1.66	5795	71.8	92930	-	0
6	4698	2.04	0.75	1.17	1.75	7482	39.5	1162	-	0
7	5239	2.27	0.76	1.29	1.76	9163	18.6	221	-	0
8	5177	2.32	0.73	1.44	1.62	10038	11.0	133	9.25-15.5	0.26
9	5153	2.35	0.72	1.59	1.48	10581	7.3	101	5.35-16.5	0.50
10	5139	2.36	0.71	1.74	1.36	10953	5.2	84.0	3.45-17	0.60
11	5129	2.37	0.71	1.87	1.27	11223	3.93	73.1	2.45-17.5	0.66
12	5121	2.37	0.71	2.00	1.19	11429	3.07	65.5	1.815-18	0.70

[a] Forward shock expansion parameter.

[b] Free expansion velocity of ejecta core-envelope boundary.

[c] Time following explosion when reverse shock enters ejecta core.

[d] Time when blast wave solutions are connected.

[e] Time interval for which ejecta passing through the reverse shock cools to optically emitting temperatures within 320 years.

[f] Mass of gas that can cool to optically emitting temperatures within 320 years of explosion.

Models modified to give same blast wave radius and core density

Table 1. Models $r_b = 2.35$ pc, $\rho_{core} = 2.25e6$ g cm^{-3}s^3, and $\rho r_b^2 = 14$ H atom cm^{-3} pc^2

n	M_{ej} $M_\odot$	E_{51} 10^{51} ergs	v_b (320yrs) km s^{-1}	r_b (320yrs) pc	η[a]	r_r (320yrs) pc	r_b/r_r	$M_{ej}\,(n-3)\,/n/v_{core}^3$[b] g cm^{-3}s^3
5.5	1.815	4.15	5134	2.345	0.716	1.28	1.92	2.146e6
6	1.815	2.8	5395	2.347	0.752	1.21	1.94	2.248e6
7	1.875	2.15	5338	2.349	0.744	1.29	1.82	2.256e6
8	1.95	2.05	5212	2.349	0.726	1.44	1.63	2.223e6
9	2	2	5153	2.345	0.719	1.59	1.48	2.240e6
10	2.035	1.985	5130	2.348	0.715	1.73	1.36	2.238e6
11	2.065	1.965	5105	2.347	0.712	1.85	1.27	2.267e6
12	2.075	1.95	5085	2.347	0.709	1.96	1.20	2.267e6

[a]Forward shock expansion parameter.

[b]Ejecta core density in velocity space.

Survival of Knots

Instabilities will shred knots over a few knot crossing times (~50 yrs, comparable to the lifetime of optical knots) if the knot is significantly overdense (or underdense).

Knots can survive the lifetime of Cas A as knots if they were not more than a few times more dense than their surroundings.

We believe knots appear as such because of their composition: heavier metals have higher emissivities via line emission.

X-ray knots are not the same as the optical knots, which are known to be dense.

Estimate of Progenitor Mass

Most of the stellar wind is from red supergiant phase lasting $\sim 2 \times 10^5$ yr at a rate:

$$\frac{\mathrm{dM}}{\mathrm{dt}} = -4\pi\rho\, r^2 v_w = 3\times10^{-5}\left(\frac{\rho\, r_b^2}{1\,\mathrm{H\ atom\ cm^{-3}\ pc^2}}\right)\left(\frac{v_w}{100\ \mathrm{km/s}}\right)\mathrm{M_O/yr}$$

Using a wind speed of 20 km/s for slowest QSF (van den Bergh & Kamper 1985), we estimate 17-20 solar masses for the total mass lost in the red supergiant phase.

A short phase of expansion into a more tenuous wind from Wolf-Rayet progenitor is suggested by slightly higher speeds and lower radii in our models than in Delaney and Rudnick (2003).

More Constraints on Progenitor

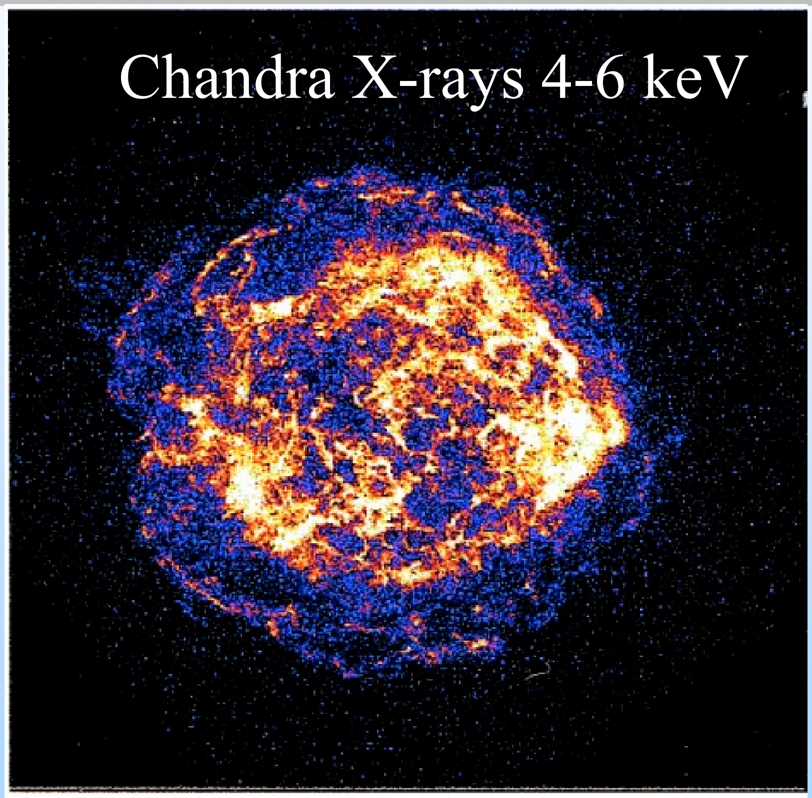
Fast wind phase is limited in length by need to allow radiative instabilities that form the optically emitting knots, so we can neglect the mass of its wind.

To the red supergiant wind mass, add observed mass of ejecta (2 solar masses; e.g., Willingale et al. 2003) and the mass of a neutron star (2 solar masses) to get 20-25 solar masses for the progenitor.

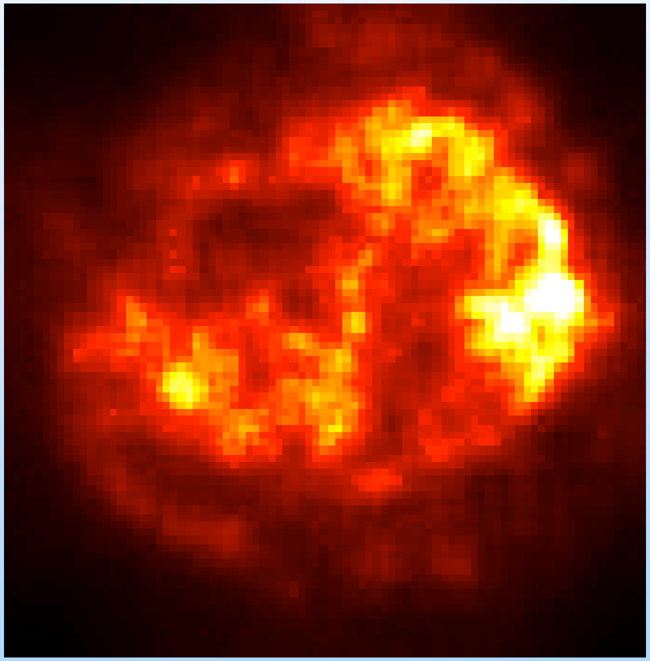
This mass is consistent with estimates based on the ^{44}Ti mass inferred from gamma-ray observations (Iyudin et al. 1994, Vink et al. 2001, Vink & Laming 2003) compared with calculations (e.g. Timmes et al. 1996)

Cas A in X-ray 4-6 keV, 8-15 keV cont.

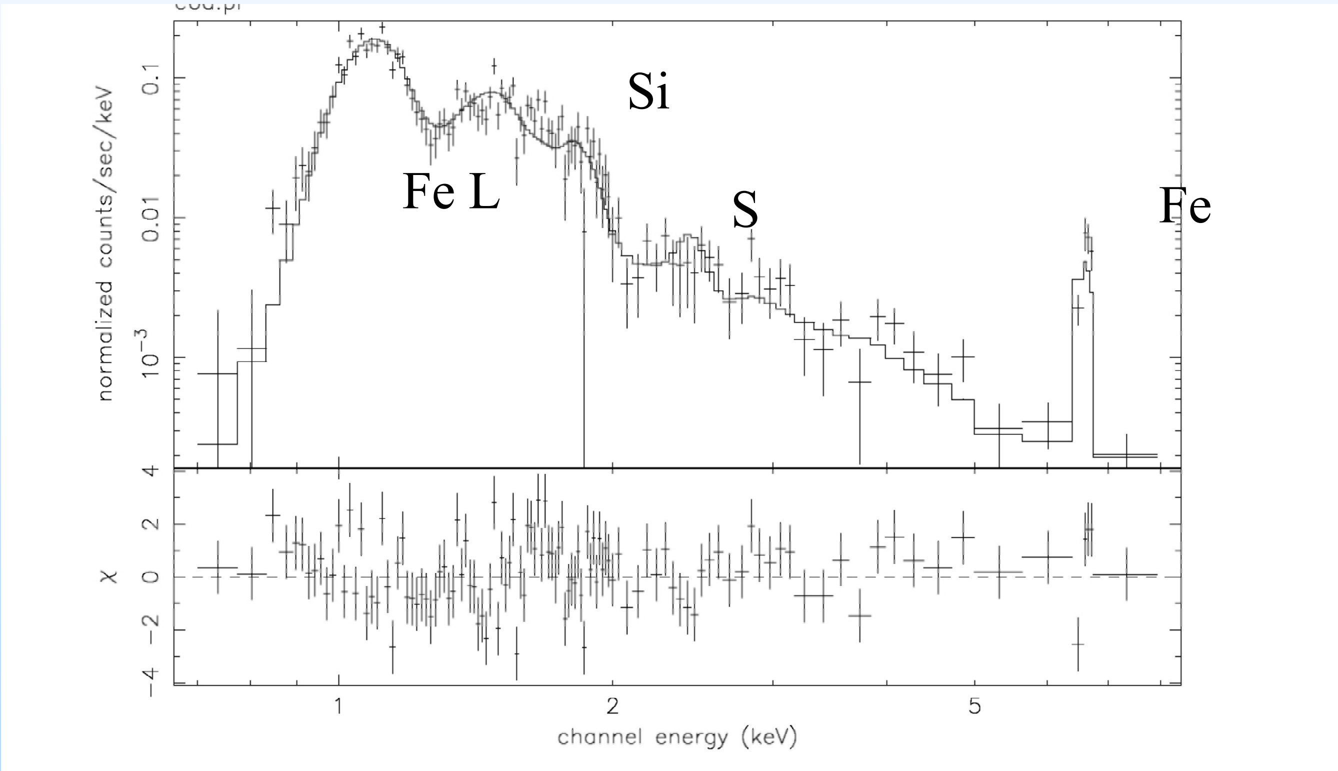
(Gotthelf et al. 2001, ApJ, 552, L39, Bleeker et al. 2001, A&A, 365, L225)



XMM-Newton 8-15keV



Spectrum of extremely Fe rich region c6a, local bkgd subtracted



Fe/Si=12 solar

n_et=2.7-5.5e11 for Fe 2e10-1.2e11 s/cm^3 for Si kT=1.7 keV.

Did alpha-rich freeze-out occur here?